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APPLICATION OF MODEL TESTS TO THE DETERMINATION OF LOSSES RESULTING FROM THE TRANSMISSION OF AIR AROUND A MINE SHAFT-BOTTOM BEND

BY

CLOYDE M. SMITH

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I. INTRODUCTION

1. *Investigation by Means of Models.*—Within the past decade or two there has been a widespread increase in the use of models to predict and to investigate the performance of full-scale appliances. While a great diversity of problems has been approached by this means, models have reached their highest development and widest application in problems involving the flow of fluids, notably in aeronautics and hydraulics.*

The recent increase in the use of models is attributable to a growing appreciation of the economy and expediency with which proposed designs can be tested or new designs developed, coupled with a better understanding of the principles of similarity† which underlie all model tests. Such use has been further stimulated by the many recent researches which have greatly advanced our knowledge of the flow of fluids.‡

While it appears that little use has been made of models in attempting to solve the problems of mine ventilation, two instances may be noted. In one of these,¶ a $\frac{1}{64}$-scale model was made of a portion of a straight aircourse in which the resistance to the flow of air had been determined underground. In the other** a one-foot square duct was lined with timber sets at various spacings and tested at each spacing. However, neither of these experiments established a completely satisfactory correlation between the results of model testing and actual mine data.

2. *Object and Scope of This Investigation.*—In view of the attractive possibilities of models as a means of solving some of the major problems which arise in connection with mine ventilation, such as the

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*"Use of Models in Aerodynamics and Hydrodynamics," O. G. Tietjens; Trans. A.S.M.E. vol. 54, No. 8, pp. 225-233, Sept. 30, 1932.

†L. Bairstow, "Applied Aerodynamics," Chapter VIII, 1920.

‡"Recent Results of Turbulence Research," L. Prandtl; Technical Memorandum, No. 720, National Advisory Committee for Aeronautics, Washington, 1933. (Translation from German with bibliography.)

¶"Calculation and Measurement of Air Flow in Mines," J. L. Hodgson; Engineering, vol. 122, pp. 58-9, 1926, and "Underground Tests on the Flow of Air at Rockingham Colliery," Douglas Hay and W. R. Cooke; Transactions of the Institution of Mining Engineers, London, vol. LXXI, part 2, pp. 337-365, 1926.

**"Experiments on the Flow of Air in Ducts," W. E. Cooke and I. C. F. Statham; Transactions of the Institution of Mining Engineers, London, Vol. LXXIII, Part 1, pp. 78-103, 1927.

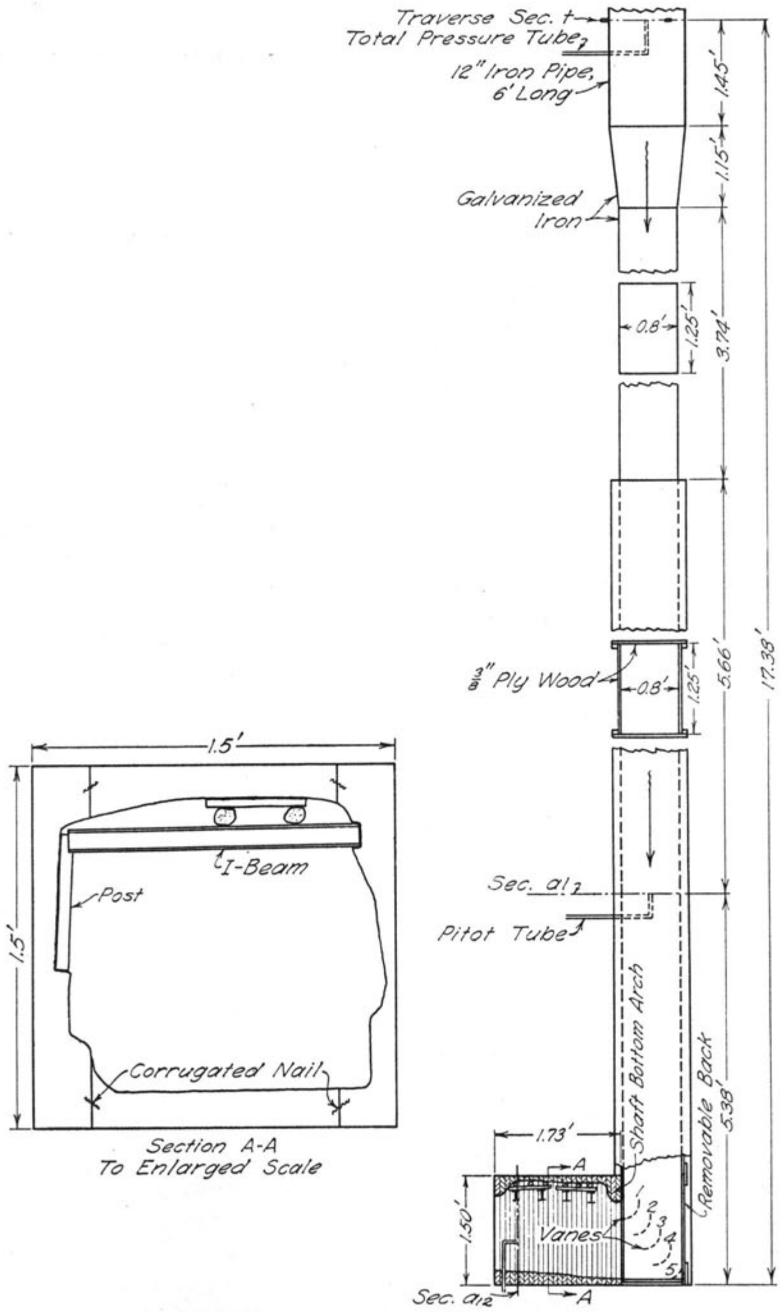

Fig. 1. Elevation of Model and Air Duct

best design for bends, splits, junctions, and air crossings, an attempt was made to see how closely certain losses already measured underground could be duplicated in a small-scale model.

The best underground data available were those relating to the shaft-bottom bend in which vanes were recently installed.* A one-tenth scale model of this air shaft bottom was made and tested, both without and with vanes, and the results were compared with those which had been observed underground at corresponding conditions of flow.

3. *Acknowledgments.*—This work was carried on as a part of the regular work of the Engineering Experiment Station, of which ACTING DEAN A. C. WILLARD is acting director, and the Department of Mining Engineering of which PROF. A. C. CALLEN is the head.

II. MODEL AND AUXILIARY APPARATUS

4. *Model.*—The model consists of three parts: (a) the lower part of the air-shaft compartment which leads into the shaft bottom, (b) the shaft bottom proper, and (c) the aircourse, which leads from it. The aircourse is known, in the mine, as the Main West aircourse (see Fig. 2, Bulletin 249). That part of the model which represents the shaft is made of $\frac{3}{8}$-inch ply board, as shown in Fig. 1, the inside dimensions of the model being one-tenth of the corresponding mine dimensions.

The concrete arch at the outlet of the shaft, (Fig. 2, Bulletin 249) was simulated by cutting a progressive series of arches out of thin white pine boards, ten thicknesses being required to represent the wall, which is 2.3 ft. thick. The shaft outlet had been cross-sectioned in four vertical north-south planes, and from the resulting four diagrams it was possible to interpolate, with a reasonable degree of accuracy, the shape of the arch for the successive wooden laminae used in the construction of the model. After the laminae had been glued and nailed together, the triangular gaps beneath their fiducial edges were filled in and the entire surface was smoothed with modeling clay. Figure 2 illustrates the model of the shaft bottom with the arch in place.

The model of the Main West aircourse was constructed of a series of rectangular frames of white pine boards 0.067 ft. thick and from 0.2 to 0.3 ft. wide, each frame being 1.5 ft. or more in outside di-

*"The Effects on Mine Ventilation of Shaft-Bottom Vanes and Improvements in Aircourses," Univ. of Ill. Eng. Expt. Sta. Bul. 249, 1932.

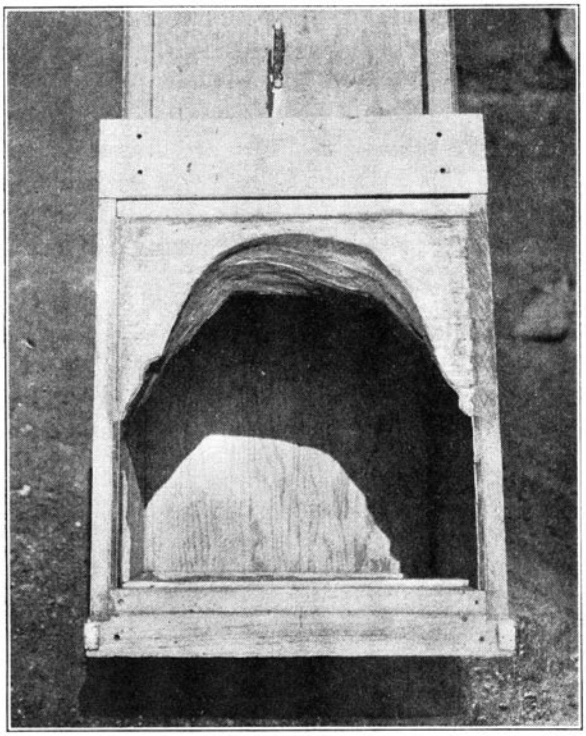

FIG. 2. MODEL OF SHAFT-BOTTOM

mensions. The outline of an entry cross-section was cut from the inside of each frame, as shown in Figs. 1 and 3. The outlines were obtained either directly from the underground cross-sections (Fig. 2, Bulletin 249), or by interpolation between them.

The model vanes were cut from 23-gage sheet tin which is 0.00189 ft. thick. Inasmuch as the mine vanes* were 16-gage, or 0.00502 ft., thick, the model vanes were not to scale, being, relatively, about 3.8 times too thick. It was felt that this discrepancy would not appreciably affect the flow of air, and that the greater thickness was needed to minimize distortion of the vanes at high air speeds. Instead of attempting to simulate the supporting angle irons used in the mine, three tabs about ⅜-inch square were left on each end of each vane. These tabs were drilled and turned 90 degrees into a plane normal to the axis of the vane, making them coincide with the east to west walls of the shaft. After the position of the end of each vane had been marked on

*Univ. of Ill. Eng. Expt. Sta. Bul. 249, pp. 28-30.

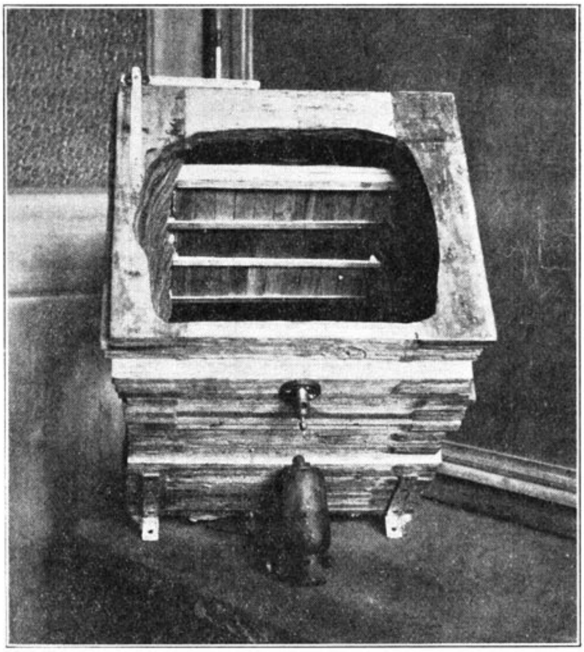

FIG. 3. MODEL OF MAIN WEST AIRCOURSE

the walls according to the relative dimensions of Fig. 13, Bulletin 249, the model vanes were fixed in place with small round-headed screws.

Tests were made with the vanes in the design form, then the vanes were deformed to conform as nearly as possible to the shape of the mine vanes.* Figure 4 shows the vanes before, and Fig. 5 shows them after deformation.

A removable floor, made up of strips 0.1 ft. wide and running east-west, was provided for the sump, as the mine sump was floored in this manner with 2 × 12-in. lumber just before the vanes were installed.

5. *Auxiliary Apparatus.*—Air was forced or drawn through the model by a centrifugal fan, which was direct-connected to a variable speed d-c motor. A modified form of Ward-Leonard control was used for the motor, which permitted it to operate over a wide range in speed.

By suitable connections the fan discharged into a round duct which terminated in a six-foot piece of 12-in. iron pipe, in which was mounted an impact tube, as shown in Fig. 1. This tube was movable

*Univ. of Ill. Eng. Expt. Sta. Bul. 249, p. 30 and Fig. 14.

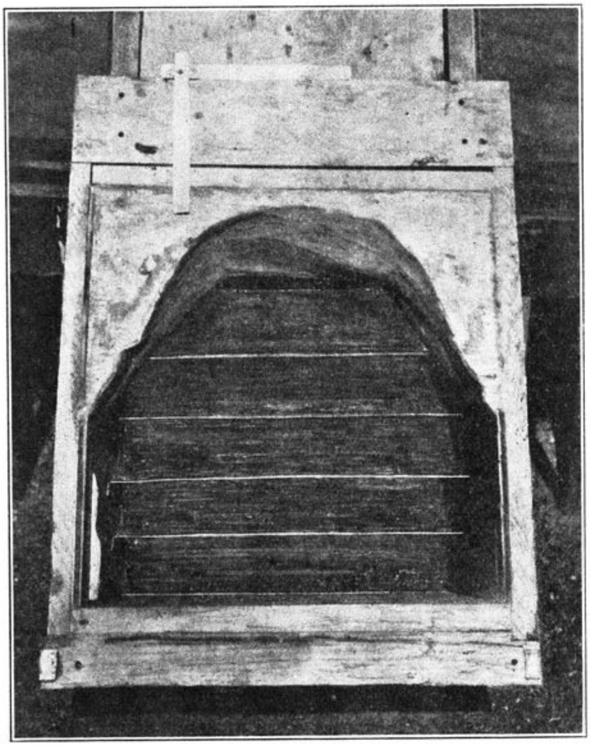

FIG. 4. VANES IN DESIGN FORM

so that its port could be placed anywhere along one diameter of the pipe. Three static pressure ports were equally spaced about the circumference of the section through the port of the impact tube. Interconnected, they gave the effect of a piezometer ring. The difference between the static pressure which they transmitted and the total pressure transmitted by the impact tube was the velocity pressure at the port of the impact tube.

This equipment permitted a velocity-pressure traverse to be made along one diameter of the air stream. Provision was made for traversing a second diameter at right angles to the first, as provided in the standard fan-testing code* by rotating the iron pipe 90 degrees about its longitudinal axis. The traverse section will be referred to as section *t*. From the end of the iron pipe an adapter conducted the air from the circular pipe to a rectangular galvanized-iron duct, which led to the wooden model (Fig. 1).

*"Fan Engineering," 3d Edition, p. 573, 1933.

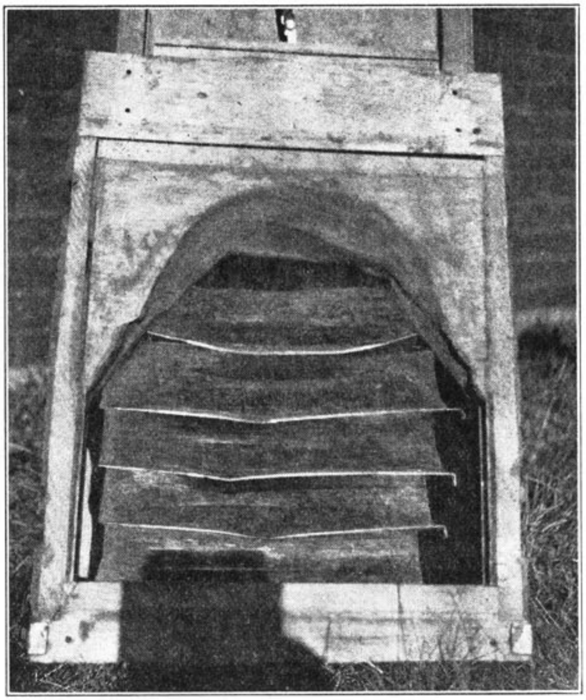

FIG. 5. VANES IN MINE FORM

All pressures were read on inclined differential gages. These, with accessory equipment, have been described previously* in Bulletin 158.

III. TESTING METHODS

6. *Determination of Rate of Flow.*—In testing the model the rate of air flow for each fan speed was calculated from readings of the center velocity pressure at section t by means of a center constant, which is the ratio of the mean velocity of flow through section t to the velocity at the center of that section. This center constant $\left(\frac{V_m}{V_c}\right)$ was established by traversing section t at different fan speeds, with the model in place, as shown in Fig. 1.

By following the routine calculations specified in the fan-testing code† a mean center constant of 0.924 was derived. This permitted

*Univ. of Ill. Eng. Expt. Sta. Bul. 158, p. 8.
†Op. cit.

center velocity pressure readings at section t to be translated directly into the rate of air flow, which is expressed in cubic feet per minute.

7. *Measurement of Pressure Losses.*—In the mine the losses between two arbitrarily located cross-sections were attributed to the shaft-bottom bend. These sections were section A_1, in the shaft, 51.5 ft. above the sump, and section A_{12}, in the Main West aircourse, 22.7 ft. west of the east wall of the shaft. In the model these distances are 5.15 and 2.27 ft., and the sections are designated as sections a_1 and a_{12}, respectively.

In section A_1 in the mine a straight pitot tube was supported along the center line of the shaft by means of a 2×4-inch board suspended diagonally across the shaft. No attempt was made to simulate this method of support in the model, but a curved pitot tube was inserted along the short axis of the model section and fixed with its static ports at the center of section a_1. The take-off tube used underground in section A_{12} was more closely simulated in the model by bringing a curved static-pressure tube up through the floor and fixing it with its ports at the point in section a_{12} corresponding to the take-off point in section A_{12}. It is thought that the deviations from strict geometrical similarity involved in this mode of pressure take-off were not sufficient to affect significantly the registration of the static-pressure differential between the two sections.

Inasmuch as the total pressure loss between these two sections can be calculated from the observed static-pressure differential between them, and the rate of flow, their cross-sectional areas being known, it was only necessary to read two differential pressures in testing, i.e., the center velocity pressure at section t, and the static-pressure differential between sections a_1 and a_{12}.

For each model condition (with and without vanes) readings were taken for each of five or six fan speeds at rates of flow ranging from about 1000 to 3000 ft. per min. in the shaft. The latter figure represents the maximum capacity of the fan.

Psychrometric observations accompanied each test, and all pressures were converted to a basis of air of standard unit weight, 0.075 pound per cubic foot.

IV. Results of Tests

8. *Direct Comparison of Losses.*—The losses incurred in forcing air through the model are compared graphically with those of the mine

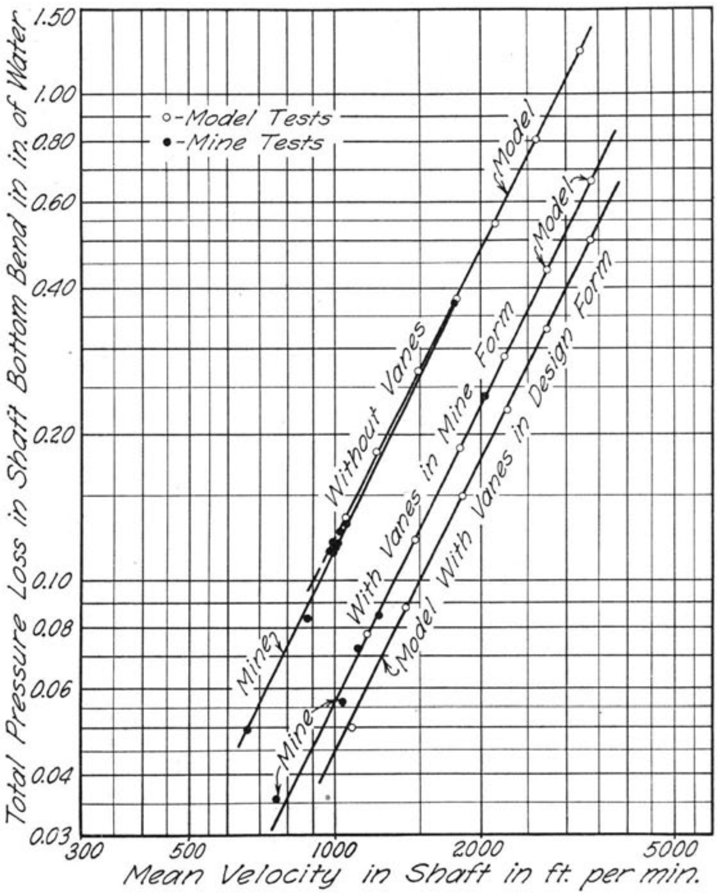

FIG. 6. RELATION BETWEEN TOTAL PRESSURE LOSS AND MEAN VELOCITY IN SHAFT

shaft-bottom in Fig. 6, where the total pressure loss between sections a_1 and a_{12} is plotted logarithmically against the mean velocity in the shaft. A typical test is represented for each of the three major test conditions, (a) without vanes, (b) with vanes in mine form and (c) with vanes in design form. The mine data for conditions (a) and (b) are included, there being no such data for condition (c). In both cases the model losses were slightly greater than, or in agreement with the mine losses.

The bottom curve shows that further savings would have been effected in the mine had it been possible to install the vanes in their design form (see Bulletin 249, p. 30).

9. *Reynolds' Number.*—Figure 6 compares the total pressure loss in the model with that in the mine at like mean velocities, but this is not in accord with the laws of dynamic similarity* which are applicable to this case. They require that the resistance of the model be compared with that of the mine at like values of Reynolds' Number,† $\frac{VD}{\nu}$. Here

V = mean velocity of air flow, ft. per sec.
D = diameter of the conduit, ft.
ν = kinematic viscosity of air, ft.^{2} per sec.

Reynolds' Number is, thus, a dimensionless coefficient, i.e., for a given situation it has the same value in whatever self-consistent set of units (e.g., English or metric) the dimensions are expressed. For air, ν has a mean value of 0.00016 ft.^{2} per sec. As the only geometrically regular part of the model is the shaft, and since it is rectangular in cross-section and its true diameter is less easily determined than its hydraulic radius, the latter has been used to derive D in computing Reynolds' Number. This is conventional procedure,‡ four times the ratio of the cross-sectional area to the perimeter of the conduit being used for D. For the mine this is $\frac{4 \times 100}{2 \times (8 + 12.5)} = 9.77$ ft., and for the model it is one-tenth as great, or 0.977 ft. Dividing these values by ν gives the following values for Reynolds' Number:

for the model shaft............................6100V
for the mine shaft............................61000V

This shows clearly that, to satisfy the requirements of the laws of dynamic similarity, which specify the same Reynolds' Number for model and full scale part, it would have been necessary to make the model tests at ten times the mean velocity of the mine tests with which they were to be compared. Inasmuch as the minimum mean velocity in the mine shaft was about 12 ft. per sec. (Reynolds' Number = 733 000) while the maximum obtainable in the model shaft was about 55 ft. per sec. (Reynolds' Number = 336 000), it was not possible to get the same Reynolds' Number for the model and the mine, so that the requirements of dynamic similarity were not fully met.

Unavoidably, this condition has been the rule rather than the exception in model testing,¶ 10- to 20-fold extrapolations of the model

*Tietjens, op. cit.
†Ibid.
‡Hay and Cooke, op. cit.
¶"The N.A.C.A. Variable-Density Wind Tunnel," Eastman N. Jacobs and Ira H. Abbott, Report No. 416, p. 31, Nat. Advis. Com. for Aeronautics, 1932.

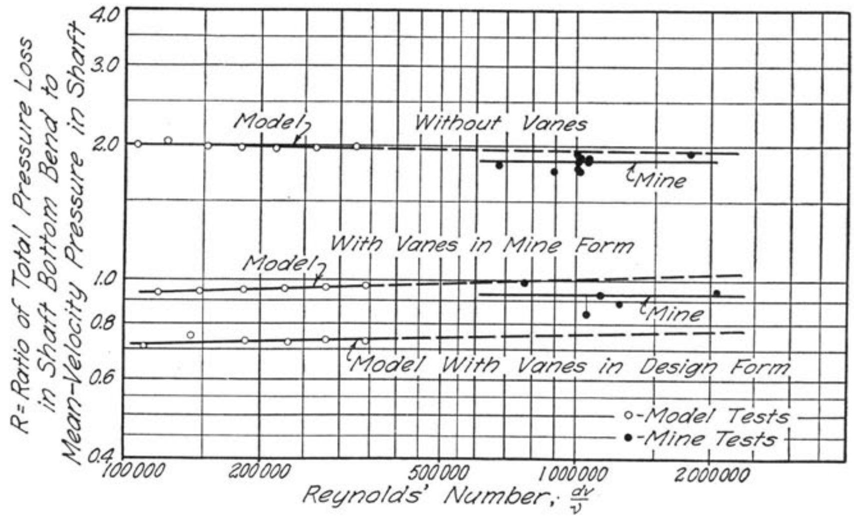

FIG. 7. RELATION BETWEEN COEFFICIENT OF RESISTANCE AND REYNOLDS' NUMBER

values having been found permissible in favorable cases. In this case, a 3-fold extrapolation would bring about a satisfactory overlap of the model and the mine values of Reynolds' Number. Such extrapolations are permissible when the flow is well beyond its critical stage or stages* and has attained a stable state of turbulence. Under these conditions the coefficient of resistance to flow is nearly independent of the Reynolds' Number.

10. *Coefficient of Resistance.*—The foregoing discussion of Reynolds' Number has served only to establish a basis on which to compare the resistance of the model and its prototype. It has not dealt with the resistance itself. Just as with Reynolds' Number, it is desirable to express the resistance in terms of a dimensionless number. The ratio of the total pressure loss to the mean-velocity pressure in the shaft has been used as a coefficient of resistance, R. Both being pressures, measured in inches of water, their ratio is dimensionless.

11. *Relation Between Coefficient of Resistance and Reynolds' Number.*—The ratio R is plotted logarithmically against the Reynolds' Number in Fig. 7 for two mine conditions and three model conditions. The mine conditions are: without vanes, and with vanes in the mine form. A model condition corresponding to each of these is shown, and an additional one with the vanes in the design form.

*Reynolds, Osborne, Phil. Trans. Roy. Soc., 1883.

In contrast with Fig. 6, in which the slope of the lines is about 2.0, the curves of Fig. 7 are nearly horizontal. They would be strictly so if the total pressure loss varied as the square of the mean velocity, because the resistance is expressed as the ratio of the total pressure loss to the mean-velocity pressure, which in turn varies as the square of the mean velocity, so that, if the total pressure loss also varied in this way, the ratio R would be a constant, and independent of V and of Reynolds' Number. Where the curves of Fig. 7 slope down to the right, as for the model without vanes, the total pressure loss varies as a power of the mean velocity a little less than 2.0, the converse being true where the curves slope upward.

The satisfactory alignment of the model test points indicates stability of flow. The scattering of the mine points is probably attributable to errors in measuring small fluctuating pressures, rather than to actual flow characteristics. The mine points are more scattered in Fig. 7 than in Fig. 6 because the steep slope of the curves of Fig. 6 tends to obscure vertical deviations from the mean line; whereas such deviations appear in full effect in Fig. 7. Due to the scattering of the mine points, no attempt has been made to establish a sloping mean line, a horizontal line having been arbitrarily drawn through the mean value of the resistances for each condition.

Extension of the model curves to the range of mine values of Reynolds' Number shows that for normal underground flow (Reynolds' Number about 1 000 000) the model resistances were a few per cent greater than the corresponding mine resistances. They are summarized as follows:

Condition	Coefficient of Resistance		Excess of Model Resistance Coefficient over that of Mine
	Mine	Model	per cent
Without vanes........	1.86	1.95	4.8
With vanes in mine form..........	0.93	1.01	8.6

The fact that the coefficients of resistance obtained from the model are greater than those obtained directly from the mine might at first seem surprising, especially as the surfaces of the model are probably relatively smoother than the mine surfaces; but the increase in resistance coefficient with a decrease in Reynolds' Number here noted is in agreement with what is observed in the testing of airfoil models and other aerodynamic bodies, and is probably attributable to what is termed "scale effect." The more nearly the scale of the model approaches that of the mine the more nearly will the model coefficients agree with those from the mine.

Despite this discrepancy the order of agreement between the model test and the mine results is such as to indicate that useful data can be expected from small-scale models of the distinctive parts of underground aircourses.

The third model condition tested, i.e., with the vanes in the design form, is an illustration of this. The lowest curve of Fig. 7, extrapolated to the mine range shows that the coefficient of resistance could have been further reduced from 0.93 to 0.76, an additional 18 per cent, had it been possible to install the vanes in the mine without distortion. This would have increased the net annual savings attributable to the vanes from $200 to nearly $240 (see Bul. 249, p. 31).

Inasmuch as this design was an arbitrary adaptation of certain industrial designs, rather than an attempted optimum solution for the case at hand, the model may serve as a means of working out the best means of deflecting the air current from the vertical shaft into the horizontal aircourse.

12. *Reversed Flow.*—Provision is commonly made at mines for reversing the flow of air, which raises the question as to what effect such a reversal might have on the mine resistance. Since the passageways of a mine are usually irregular, offering an unsystematic sequence of expansions and contractions to the air stream, and since a given expansion or contraction will ordinarily offer a different resistance to flow in one direction from that experienced in the other, the total mine resistance may be expected to be different under reversed and normal air coursing, respectively.

To illustrate this the model was installed on the intake of the fan, and air was drawn in through the entry into the shaft. For the three test conditions, without vanes, and with vanes in mine and in design form, the resistance of the shaft-bottom under reversed flow was found to be from about two-thirds to one-half of that with normal flow. Since the cross-sectional area of the shaft is appreciably less than that of the entry, the air stream contracts in going around the bend under reversed flow, but expands under normal flow. As contractions normally occasion less resistance than corresponding expansions, the result obtained is consistent with expectations.

No generalizations can be made from this case, however, beyond the statement that the resistance of a mine under reversed flow may be expected to differ from that under normal flow. To what extent,

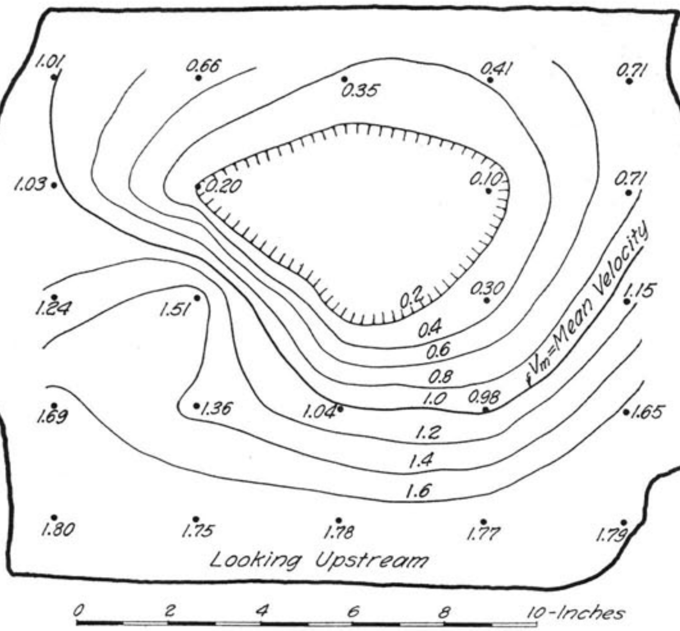

FIG. 8. ISOVELS, SECTION A_{12} WITHOUT VANES

or in which direction, it would differ would have to be determined for each case individually.

13. *Velocity Distributions.*—Since the mine shaft was inaccessible for exploration nothing is known of the velocity distribution or lines of flow within it, save that the center constant $\left(\frac{V_m}{V_c}\right)$ at section A_1 was greater than unity, showing that a less-than-average velocity prevailed at the center of the section (see Bul. 249, p. 37). This was not true in section a_1, in the model, where the center constant was less than unity. This shows that there was some dissimilarity between the model and the mine with respect to the velocity distribution in the shaft. Whether or not this affected their comparative resistances is not known.

The distribution of velocity within the entry model was investigated by subdividing section a_{12} into twenty-five subsections, as shown in Fig. 8, and traversing it in the manner usually employed for underground work (see Bul. 158, p. 17). In this figure the locus of the mean of the velocities found at the twenty-five traverse points is indicated by the line designated V_m, or 1.0. The remaining lines connect

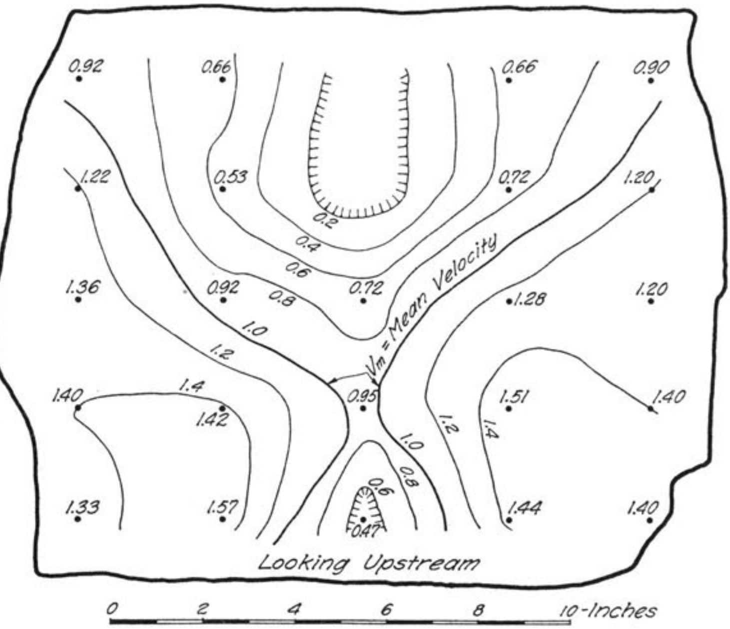

FIG. 9. ISOVELS, SECTION A_{12} WITH VANES IN MINE FORM

points having equal velocities bearing the designated ratio to the mean velocity.

In many respects Fig. 8 shows the converse of a normal velocity distribution, as its minimum velocities are near the center and its maximum velocities are near the periphery. The high velocities near the floor are a clear indication that most of the air coming down the shaft was carried to the lower part of the shaft bottom and flowed out along the floor of the entry.

In comparison with Fig. 8, Fig. 9 shows how the vanes of the form used in the mine affected the velocity distribution in section a_{12}. The high-velocity area has been shifted from the floor to the ribs, leaving a vertical low-velocity area down the center. The distribution was considerably improved by using vanes of the design form, as shown in Fig. 10. The velocity in the lower half of the section is nearly uniform, and there is only a small low-velocity area in the upper central part of the section.

14. *Lines of Flow.*—The lines of flow within the model were observed with a one-inch piece of thread attached to the end of an L-shaped piece of stiff wire.

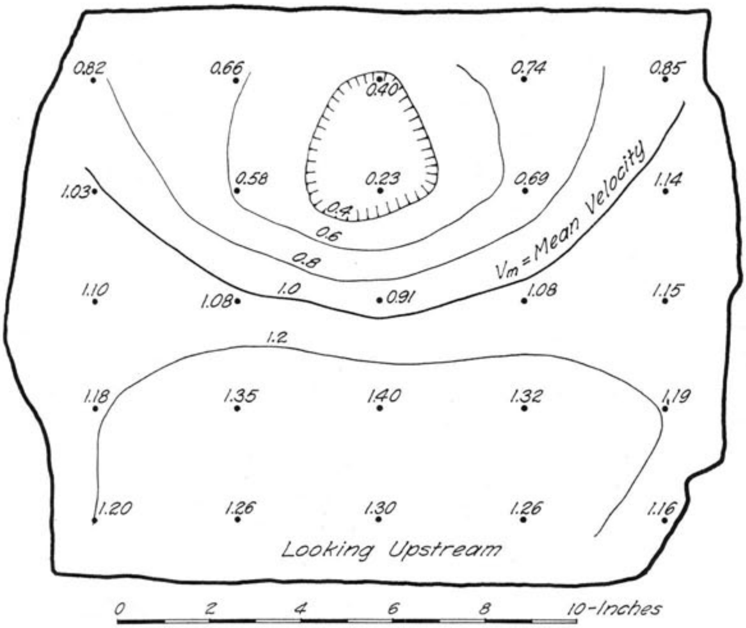

FIG. 10. ISOVELS, SECTION A_{12} WITH VANES IN DESIGN FORM

Without the vanes, the lines of flow in the model were quite like those in the mine (see Bul. 249, Fig. 19). The two eddies in the back corners of the shaft-bottom seemed to be more active in the model than in the mine, their currents rising in each corner to the mid-height of the entry. All of the air discharging from the shaft-bottom into the aircourse had a downward component, except that immediately adjacent to the sides.

In the form used in the mine the vanes were so deformed that their central parts more nearly approached flat sheets placed at 45 degrees to the horizontal than circular arcs. They were true to design at their ends, however.

The air flowed over vane No. 1, (see Fig. 1) in good lines, but discharged at a downward angle ranging from a few degrees at the ends of the vane to about 45 degrees centrally. Good flow conditions also prevailed in the lower one-fourth of the space between vanes 1 and 2. In the remainder of the space eddying became increasingly marked as the bottom of No. 1 vane was approached. In fact, there was a re-entry of air under the lower part of No. 1 vane. The flow over vane No. 3 was much better than that over No. 2. There was some eddying just under vane No. 2 but no re-entry of air, as under No. 1. The best flow conditions prevailed between vanes 3 and 4, that between vanes 4 and 5 being rather sluggish, with some eddying along the surface of vane No. 5.

With the vanes in the design form, the flow over vanes 1, 2, and 3 was considerably improved by a reduction in the downward components of discharge and in the re-entry or eddying just under the vanes.

In the model entry there was a regressive current of air flowing east between the roof and the lagging near it (see Fig. 1). This air was supplied by the main current at the west end of the lagging and discharged into that current just west of the arch. A second bad feature of the flow in the entry was the existence of a helix of flow in each upper corner. Both helices were dominantly progressive in their flow, but their rotation was unmistakable. The north one rotated counter-clockwise and the south one clockwise as viewed in the direction of flow. Such a pair of helices is frequently visible in a stream of smoke issuing into the wind from a vertical stack, and there are indications that helices of this kind are common in mine airflow. In the case of the model entry they are thought to be due to the crowding of the air out of the high-velocity zone along the floor, up along the ribs into the upper, low-velocity zone. This leaves an upper central zone of eddying flow, which persisted under the best flow conditions which were obtained (see Fig. 10).

This analysis of the flow of air through the model shows that the vanes greatly improved the transmission of air around the shaft bottom bend, but that their greatest effectiveness was confined to the outer and lower currents. Considerable further improvement is desirable in the inner and upper currents. This probably could be effected by redesigning the arch and the upper part of the vane structure.

V. Summary and Conclusions

15. *Summary and Conclusions.*—In line with the increasing use of models in other types of work, a one-tenth scale model of a mine shaft bottom of known resistance to airflow was tested under various conditions, to determine the validity of model tests in comparison with full scale tests.

Air was forced through the model by a variable-speed centrifugal fan, the rate of flow being determined by traverse or center velocity pressure readings in the circular duct leading to the model. This rate varied from about 1000 to 3000 feet per minute in the shaft for each test. Pressure losses were determined between a section in the shaft and one in the aircourse, each of which corresponded in position and configuration to a pressure-measuring section which had been used in the mine. An arbitrary coefficient of resistance was established to serve as a function of Reynolds' Number. It is the ratio of the total pressure loss to the mean-velocity pressure in the shaft. It was plotted logarithmically against Reynolds' Number both for the model and the mine (see Fig. 7). Extrapolation of the model results into the range of mine Reynolds' Numbers shows the model resistance coefficient to be a few per cent greater than that of the mine for comparable conditions of flow. This might indicate some lack of similarity between the model and the mine, or between their respective flows, but is probably due mainly to "scale effect."

The agreement was sufficiently close to indicate that useful results can be expected from small-scale models in designing such important units as bends and splits in the aircourses. Their use should also aid in the selection of a type and spacing of supporting timbers to combine the maximum of support with the minimum resistance to the passage of air.

While vanes, as installed in the mine, reduced the resistance of the shaft bottom bend 50 per cent, the model tests indicated that if they had been installed in the design form they would have reduced the resistance more than 60 per cent. It also showed that the resistance of the bend would be considerably less under reversed flow than it was under normal flow, either with or without vanes.

Finally, the model provided a ready means of analyzing the flow of air through the bend, and indicated where further improvements in the design of the bend might be made.

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